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Final Report

Hydrologic and Geomorphic Characterization and Development of the Actively Incising Indian Creek Valley, Central Nevada

Contract: 02-CS-11222074-091
(WCU 5-53013)

Principle Investigators
Mark Lord and Jerry Miller
Department of Geosciences and Natural Resources Management
Western Carolina University

with

David G. Jewett, Jeanne C. Chambers, S. Reed Johnson, and Chris Ernst

Extended sections of this report were extracted from other published studies, including:

David G. Jewett, Mark L. Lord, Jerry R. Miller, and Jeanne C. Chambers. 2004. The Hydrologic System: Geomorphic and Hydrogeologic Controls on Surface and Subsurface Flow Regimes in Riparian Meadow Ecosystems in the Central Great Basin, in Great Basin Riparian Ecosystems: Ecology, Management, and Restoration. Island Press.

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SUMMARY

Riparian ecosystems generally account for only a few percent of the total land area in the central Great Basin, yet contain a high percentage of the biodiversity in the region. In many of these riparian systems, stream incision has lowered groundwater tables causing a loss in wet meadow area. The present and past geomorphic and climatic conditions cause stream incision to be pervasive, however, in some places, the incision is accelerated by land use practices. Indian Creek valley, a tributary to the upper Reese River, exemplifies these conditions. The valley contains a variety of wet meadow system types that are dissected by trenches in various stages of activity and development. In this report, the hydrology and geomorphology of distinct reaches of the valley are characterized and a conceptual model of trench evolution is presented.

In the upstream portion of Indian Creek valley, broad, gently sloping alluvial fan surfaces flank the axial valley and outcrops of bedrock are limited to high elevations along the drainage divides. Small, young alluvial fans are common adjacent to the valley floor. Downstream, the basin width narrows, and basalt associated with Black Mountain outcrops or is covered with a thin veneer of colluvium. Detailed study of the stratigraphy in Indian Creek valley shows that over the past several thousand years there have alternating periods of aggradation and degradation, probably linked to climatic variation and sediment supply within the watershed. The Indian Creek valley history is similar to other valleys in central Nevada, but the most recent history has been a more varied and dynamic.

The geologic and topographic conditions associated in the Indian Creek basin are conducive to supplying ample and steady groundwater—most likely as a discharge area of a large-scale groundwater flow system. At a reach scale, the groundwater conditions vary with valley position, geomorphic position, and degree of valley floor entrenchment. Throughout the valley, there is a strong correlation among depth to groundwater, geomorphic position, and vegetation type.

A continuum of trench sizes and forms occur in Indian Creek valley: they range from shallow, discontinuous trenches to an integrated, deep, continuous trench system. The trenches were qualitatively categorized based on shape and size characteristics into four types (A, B, C, and D). Along with size, the trench types are most easily distinguished based on how actively the trench walls are enlarging due to slumping, most likely induced by groundwater sapping. Areas of active entrenchment have walls that are steep-sided, mantled with fresh slump blocks, and are commonly sites of groundwater seeps. In one meadow complex, over 500 m of trench length developed between 1961 and 1982, resulting in a large decrease in the areal extent of wet meadows on the valley floor.

It is clear that groundwater sapping induced slope failure is important in the entrenchment of Indian Creek valley. Key conditions necessary groundwater sapping induced bank failure are present in the valley: groundwater flow convergence, surface water removal of slump debris, and a threshold bank height and strength. The smallest trenches (type A) likely represent incipient forms of larger systems, but, at present, are low-relief (< 0.5 m) because they have not incised down through the strong root zone of wet meadow soils. Trench types B and C are the most active; these trenches have cut through the root zone and have headcuts in a position to collect significant groundwater flow. There growth rate is likely controlled by the duration and frequency of surface and groundwater conditions necessary to induce bank failure and debris removal. Type B trenches are likely active only during exceptionally wet years whereas the type C trenches are likely active during most spring seasons. The most stable trenches in Indian Creek valley, type D, show little evidence bank failure caused by groundwater conditions. More recent entrenchment of the valley has resulted in a trench network that captures groundwater that would have previously fed into the large trunk trenches. It is very likely that land-use activities within the valley have accelerated and triggered some of the incision. Evidence for this is most clear at several check dams, where dug diversion channels coincide with the start of a trench.

Effective management of the area requires an understanding of the complexities of the groundwater-surface water interactions in riparian meadow systems. Further, it is necessary to understand the incision processes and sensitivity of the system to incision because of the importance of streams and trenches in establishing local base levels. Any land use activity that concentrates either groundwater or surface water is likely to accelerate the entrenchment of the valley.

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INTRODUCTION AND OBJECTIVES

Riparian wet meadow systems comprise less than 2 percent of the total land area of the Great Basin yet serve as essential habitat for many plant and animal species. Indian Creek valley, a tributary to the upstream Reese River, contains a variety of wet meadow system types that, in many places, support an abundance of the threatened Columbia Spotted Frog. Lord, Miller, and Chambers have been studying the lower portion of Indian Creek to evaluate the effects of channel incision on the hydrologic, geomorphic, and biotic systems. Study results showed that the systems are highly interdependent. In the upstream reaches of the incised valley (referred to here as the study area), the channel contains a perennial stream, groundwater flow exhibits minimal variation, and a strip wet meadow lies adjacent to the channel on the incised trench floor (Fig. 1). Downstream, willows and dry meadow species flank an ephemeral, cobble-bedded channel, and the groundwater conditions exhibit high spatial and temporal variability.

The geomorphology of the region reflects different evolutionary stages of the valley as the broad valley floor is incised by trenches that ultimately cause dramatic changes in the hydrologic and biotic characteristics of the valley. Preliminary field observations indicated that the incised reach has developed through the headward expansion of the trench and by groundwater sapping. Thus, the spatial variations that are observed along Indian Creek are likely to represent the systematic changes in the linkages between the surface and groundwater flow systems as entrenchment occurs.

The primary objectives of this study were to characterize the hydrology and geomorphology of distinct reaches of the valley, and develop a conceptual model that explains the time-space evolution of the system in response to incision. More specifically, the study was intended to:

1) Determine the geomorphic and hydrologic characteristics of distinct reaches of the Indian Creek valley that represent different evolutionary stages of a valley floor (i.e., the transition from a wet meadow system to an incised trench system with intermittent flow);
2) Determine the stratigraphic and geomorphic history of Indian Creek valley;
3) Determine the evolutionary stages of trench development, and the rates of valley entrenchment; and
4) Develop a conceptual model that explains valley evolution so that Indian Creek valley and similar systems can be managed more effectively.

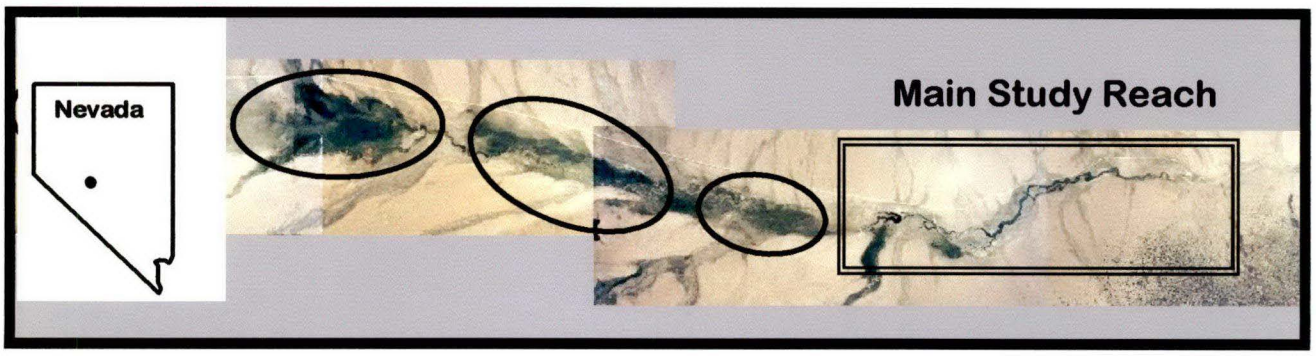

Figure 1. Index map and vertical aerial photograph of Indian Creek Valley; downstream and north to right. Wet meadows are indicated by dark areas on the photo and are enclosed; the main study reach is enclosed with a rectangle.

BACKGROUND

Riparian ecosystems generally account for a limited amount (1-3%) of the total land area in arid regions (Naiman and Decamps 1997) such as the Great Basin of central Nevada. Nonetheless, they contain a disproportionally large percentage of the region's biodiversity (Saab and Groves 1992; Hubbard 1977). Water, from both surface and subsurface sources, is essential for the occurrence and persistence of Great Basin riparian areas and other similar riparian ecosystems in mountainous regions of the western U.S. Changes in the abundance or the quality of water supporting meadow and other riparian ecosystems, whether the cause is natural or anthropogenic, have dramatic effects on ecosystem survival (NRC 2002). For example, it is generally accepted that riparian vegetation patterns are directly controlled by geomorphic and hydrologic factors (Bendix and Hupp 2000). Groundwater levels particularly influence plant species distributions (Allen-Diaz 1991; Stromberg et al. 1996; Castelli et al. 2000; Law et al. 2000; Martin and Chambers 2001). Thus, stream incision on the order of <1 to 5+ meters, brought on by climatic shifts and likely exacerbated by anthropogenic impacts, can alter species composition and vegetation patterns. It follows, then, that successful maintenance and restoration of riparian ecosystems requires a good understanding of the surface and groundwater flow regimes and their interactions (Winter et al. 1998; Winter 1999; Woessner 2000; Jones and Mullholland 2000). An important component of the Great Basin Ecosystem Management research project focuses on increasing our knowledge of the hydrology of riparian meadow ecosystems in upland watersheds of central Nevada. Research conducted to date has: (1) characterized surface and groundwater flow systems and the interactions between these hydrologic systems with respect to geomorphic/geologic setting, (2) documented the response of riparian hydrologic systems to geomorphic/incision evolution, and (3) evaluated relationships between surface water/groundwater systems and riparian vegetation patterns. Results from this research are being used to develop a framework for implementing scientifically sound riparian zone management and restoration strategies.

This report examines the geomorphic and hydrogeologic controls on riparian ecosystem hydrology of upland watersheds in the Great Basin of central Nevada. The relationships among stratigraphy and geomorphology are examined and the evolution of trench systems is evaluated. A discussion of a framework for implementing scientifically sound management and restoration strategies from a geomorphic and hydrologic perspective concludes the report.

SETTING

This research project focused on the central Great Basin. The Great Basin consists of more than 100 major hydrographic basins covering an area of approximately 500,000 km^2 (Heath

1988; Mifflin 1988). The hydrology of the Great Basin is complex due to a combination of climate, basin and range structure, and internal drainage (Mifflin 1988). In central Nevada, the physiography of the Great Basin is dominated by southwest-northeast trending fault-blocked ranges that are separated by intermontane basins. Regional groundwater flow systems in Nevada are common in large drainage basins and are characterized by regional boundary controls, discharge zones with minimal fluctuations in flow, and interbasin water transfers. Local flow regimes are characterized by: (1) small drainage areas with relatively short flow paths; (2) boundary controls consisting of local lithologic, tectonic, and topographic features; (3) surface and groundwater discharges that vary greatly both seasonally and with storm events; and (4) little or no interbasin transfers of water (Maxey 1968).

Average annual precipitation in the Great Basin ranges from 100 to 500 mm and varies greatly throughout the region. Approximately 0-16% of the annual precipitation recharges local and regional groundwater systems (Maxey and Eakin 1949; Berger 2000; Nichols 2000). Winter snowpacks in mountainous areas are the primary source of groundwater recharge in higher elevation watersheds. Melting of these snowpacks provides for increased streamflows during the springtime. As spring meltwaters decrease, groundwater baseflow becomes the primary source of water sustaining streamflows. Perennial streams carry water from the higher elevations towards the large intermontane basins. Stream discharges decrease throughout the summer and fall, except for occasional high flows brought on by large storm events. Surface water and groundwater exchanges occur along the entire length of the stream channel. Whether the stream is a gaining, losing, or flow-through system (Winter et al. 1998; Woessner 1998) varies among valley segments and stream reaches and depends on local hydrogeologic and geomorphic controls. In the Great Basin, these streams eventually become losing systems as they cross and infiltrate alluvial fans upon entering the internally drained intermontane basins, where all surface waters and groundwaters ultimately are evaporated or transpired (Mifflin 1988).

Upland Watersheds of Central Nevada

Whereas the physiographic setting of the Great Basin of central Nevada is dominated by fault-block ranges separated by intermontane basins, the geographic setting of watersheds in upland areas is quite different. Upland watersheds typically are smaller in area, ranging from a few square kilometers to more than 100 km^2, and generally occur at elevations ranging from 1750 to 3200 m. Annual precipitation also is quite variable and is orographically controlled. Higher elevations can receive precipitation in excess of 450 mm/yr. Precipitation near the mouths of upland basins is about 200 mm/yr; approximately 60% of the precipitation occurs as snowfall during the winter months.

Stream systems in upland watersheds of central Nevada consist of axial channels that are characterized by high gradients and gravel dominated beds. Peak runoff is in response to

snowmelt in late May or early June, but localized convective storms during the summer can result in transient high streamflow events. Average stream discharges range from 0.015 to 2.00 m^3/s (Hess and Bohman 1996). In general, streamflow increases downvalley due to groundwater discharge to the channel. However, groundwater and surface water interactions are variable along the entire length of the axial stream system. At the mouths of the upland basins, streamflow is dissipated through evapotranspiration, recharges to the groundwater system of the intermontane basin, and/or is diverted for irrigation purposes.

Vegetation at low to mid elevations in upland watersheds consists of Wyoming big sagebrush (*Artemisia tridentata* spp. *wyomingensis*) communities interspersed with Utah juniper (*Juniperus osteosperma*) and single leaf pinyon (*Pinus monophylla*) woodlands. At higher elevations, mountain brush vegetation, including mountain big sagebrush (*Artemisia tridentata* spp. *vaseyana*) and limber pine (*Pinus flexilis*), dominate. Riparian vegetation generally consists of stringers of quaking aspen (*Populus tremuloides*), narrow leaf cottonwood (*Populus angustifolia*), river birch (*Betula occidentalis*), and willows (*Salix* spp.) (Weixelman et al. 1996). Vegetation patterns in riparian ecosystems are controlled by both geomorphic and hydrologic factors, in particular, the depth to groundwater is important (Allen-Diaz 1991; Stromberg et al. 1996, Castelli et al. 2000; Martin and Chambers 2001). Meadow vegetation types occur along distinct hydrologic gradients and include, from shallow to deep groundwater depths, Nebraska sedge (*Carex nebrascensis*) or wet meadow, mesic meadow, dry meadow, and basin big sagebrush (*Artemisia tridentata* ssp. *tridentate*) meadow types (Weixelman et al. 1996; Castelli et al. 2000).

Indian Creek Valley

Indian Creek valley is located in the Humboldt-Toiyabe National Forest and is believed to be representative of riparian corridors within upland watersheds. Indian Creek valley (38°49'03"N, 117°30'02"W) is located within the headwaters of the Reese River basin about 60 km south-southwest of Austin, Nevada. The Indian Creek watershed covers an area of 86 km^2 and is bound by the Shoshone and Toiyabe ranges. The elevation at the study site is about 2225 m. Volcanic bedrock, mostly rhyolitic tuff, underlies the basin, and Quaternary alluvium and colluvium cover the axial valley and gentle slopes (Kleinhampl and Ziony 1985). The Indian Creek valley is generally broad and supports about a half dozen meadow complexes that exhibit varying degrees of channel incision. Upstream, channels are absent or discontinuous; wet and mesic meadows cover most of the valley floor. In contrast, downstream, wet and mesic meadows are confined to the floor of incised trenches where the groundwater table has dropped. The progressive stages of entrenchment of the meadow complexes have afforded an important opportunity to study the interdependent responses of hydrologic, geomorphic, and vegetational components of the valley system.

METHODS

Field reconnaissance and mapping was conducted to describe the geomorphic and stratigraphic setting of the Indian Creek field site. Topographic and geomorphic features, such as stream channels, terraces, valley floors, alluvial fans, and hillslopes were surveyed at the site. Geomorphic evolution of the valley was further assessed by using historic aerial photographs. In addition, ten stratigraphic sections were described to interpret the geomorphic history and hydrogeologic settings. In addition to site specific data, information collected during field reconnaissance from other riparian meadow complexes in the Toiyabe, Toquima, and Monitor Ranges of central Nevada, with similar valley floor morphologies, also have been used to clarify hydrogeomorphic relations.

Shallow groundwater flow at the Indian Creek field site was characterized based on hydraulic head (water level) data collected from a large number of piezometers and observation wells. Piezometers are small-diameter wells with a short screened section used to measure the total energy of water at a point in an aquifer, also known as hydraulic head (Fetter 2001). Observation wells generally have a longer screened section and are installed so that the water table lies within the screened section. Groundwater flows from higher to lower hydraulic head values. Thus, hydraulic head data from the piezometers and wells were used to construct water table maps and profiles.

In general, the piezometers were constructed of 1.9 cm (0.75 in) thin-walled, electrical conduit. The lower 0.5 m of the conduit was drilled with small holes to provide a "screened" section. The lower end of the conduit was then plugged with a machined drive point or carriage bolt and the piezometer was driven into the ground using a fencepost hammer to the desired depth which ranged from 0.5 to 6 m. At several locations, nested piezometers were constructed. Nested piezometers are closely spaced piezometers open at different depths in the subsurface that provide data on the vertical hydraulic gradients in the area of the nests (Fetter 2001). The nested piezometers in this study consisted of two piezometers located in close proximity, one installed to a shallow depth (0.6 – 2.6 m) and the other to a greater depth (2.3 –5.3 m) depending on the depth to groundwater. The conduit used for nested piezometers was only slotted in the bottom 20 cm of the conduit.

Locations and elevations of wells and topographic and geomorphic features were mapped using a Leica Total Station. All elevations were determined relative to a site benchmark. Reliability of survey data, particularly groundwater well elevations and locations, was assessed by repeating the survey from separate locations (where trees and other vegetation allowed a view of the sites). In general, the validation measurements were within 1 cm of the original survey

data. All maps are based on these survey data. Map accuracy was determined by visual inspection of cartographic outputs in the field.

RESULTS

Indian Creek valley contains several meadow complexes that have undergone various degrees of channel incision. The entrenchment of the valley floor is largely driven by groundwater sapping, that is, bank failure triggered by undercutting caused by groundwater seeps. Incision has caused a lowering of the groundwater table and a vertical displacement of wet meadows from the valley floor down to the trench floor. A study area was chosen in Indian valley to include different stages of incision based upon the geomorphic, hydrologic, and vegetational characteristics. A substitution of space (i.e., reach position) for time is used to predict the consequences of future incision in Indian valley; this is a commonly used approach in geomorphology and has also been used to predict the vegetational consequences of groundwater decline (e.g. Stromberg et al. 1996).

Geomorphology

The Indian Creek study site is centrally located within its watershed and is coincident in location to where the basin width decreases from about 10 km to 4 km in the downstream direction (Fig. 2). Upstream from this area, broad, gently sloping alluvial fan surfaces flank the axial valley and outcrops of bedrock are limited to high elevations along the drainage divides. The large alluvial fan surfaces are generally bouldery at the surface and are no longer active. Smaller and younger alluvial fans are common adjacent to the valley floor (Fig. 2). At the downstream end of the study site, where the basin width narrows, basalt associated with Black Mountain outcrops or is covered with a thin veneer of colluvium.

The valley floor reaches widths of hundreds of meters at the upstream end of the basin, but narrows to tens of meters downstream. Upstream, about a half dozen broad meadow complexes cover the valley floor, which are only dissected by shallow, discontinuous channels. These trench-shape channels are generally low-relief (< 50 cm), have steep-walled headcuts, and, in some places, terminate in shallow fan-like features composed of sediment deposited on the valley floor. As the valley narrows downstream, in the study site, a continuous trench, about 2.5 km in length, has been incised into the valley floor (Fig. 2). Several subparallel trenches are tributary to the main trench in the upstream portion of the study area. The main trench is rectangular in shape, up to 4 m deep, and 30 m wide; the trench size decreases downstream. Trench walls have steep sides and are blanketed with fresh slump blocks. The trench itself is not a stream channel. The trenches share some characteristics of arroyos, most notably the vertical walls formed by erosion into axial valley alluvium and the presence of a stream channel on the

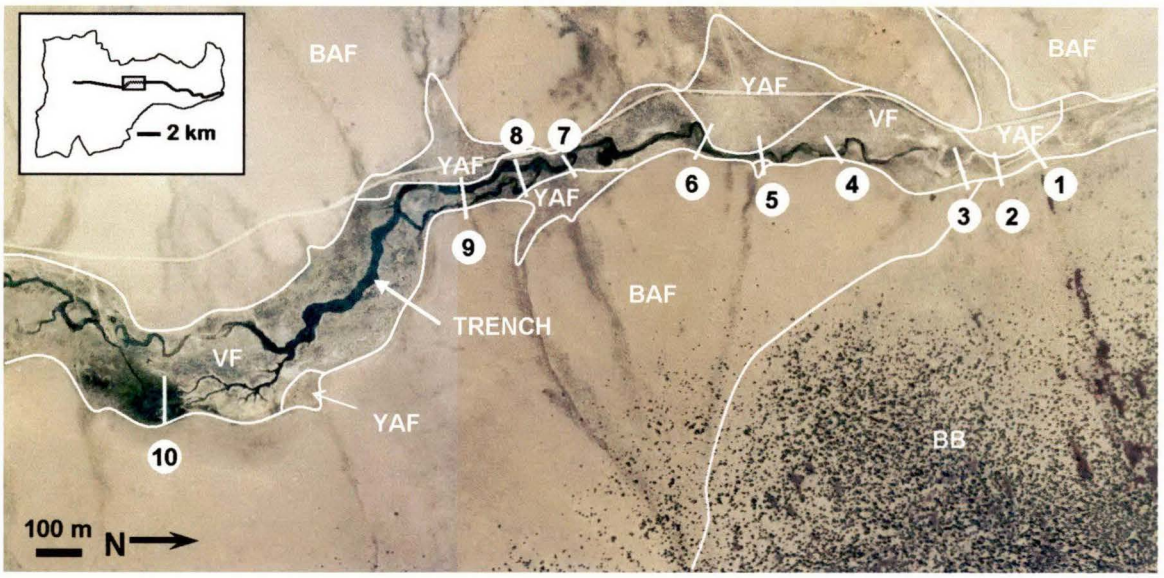

Figure 2. Study setting and design of Indian Creek valley. Index map shows watershed shape and study location. Vertical aerial photograph of Indian Creek valley shows study area geomorphic units and locations of study transects (numbered lines). Geomorphic units are VF: valley floor; TRENCH: incised trench within valley floor; YAF: young alluvial fan surface; BAF: older, bouldery alluvial fan; and BB: basalt bedrock near surface associated with Black Mountain (northeast corner of photo). Groundwater measurements and vegetative surveys were made along transects (from Jewett et al. 2004).

trench floor. However, arroyos are typically larger-scale and more continuous erosional features with the incision generally caused by ephemeral stream channels (Bull 1997; Elliot et al. 1999). Many of the trenches in Indian valley are gullies in that they are discontinuous and formed where there were no prior channels (Schumm 1999).

A small stream channel, Indian Creek, is located on the trench floor and is 0.5 to 2 m wide. Upstream within the study area, the stream bed is fine-grained and supports perennial flow. Downstream, flow is intermittent or ephemeral and the stream bed is cobbly. The stream channel form also changes in the downstream direction from well-defined, deep, wide pools connected by small runs to a wide, shallow channel. One or two low-relief (10's of cm) stream terraces are present along some reaches of the trench floor.

Stratigraphy and Geomorphic History

The geomorphic history of Indian Creek valley generally follows that found in the other valleys of central Nevada, although it appears that the most recent history has been a bit more varied and dynamic. Detailed stratigraphic and geomorphic studies, completed in upland watersheds of the Great Basin of central Nevada, demonstrate a clear linkage between climate, slope processes, channel dynamics, and riparian ecosystems (Miller et al. 2001). Furthermore, modern channel dynamics are influenced not only by the present-day climate, but by landforms and depositional events that occurred 2000 years ago. Because of the importance of past events in controlling modern processes, a detailed stratigraphic study was completed in Indian Creek valley (Fig 3). This analysis used the stratigraphic and geomorphic framework established by Miller et al. (2001) (Fig. 4). Ten stratigraphic section were described throughout the incised reaches of Indian Creek valley (Fig. 3).

Qa1/Qf1 has not been identified in the valley. However, Qa2 is locally present, particularly upstream of the monitored site within the region of the most upstream gullies. Locally, it is characterized by a weakly developed, buried soil at the top of the unit (where it is not been eroded and buried by more recent deposits), and sedimentologically consists of a massive silt or silt loam unit with abundant small (<1 cm) pebbles disseminated throughout. Locally, Qa2 contains some dark reddish brown mottles, and is vertically fractured. In other locations, sediments are dark reddish brown, a characteristic which may be the due to the erosion and redeposition of red, paleofan deposits located along the valley sideslopes in upstream areas. Organic materials in the soil at Section 5b exhibits a date of 2350+/- 70 YBP, indicating that the unit is temporally correlative to Qa2 in other watersheds in the area. Where the soil exists, the soil is commonly overlain be a thin (<0.5 cm), reworked ash. This is likely to be one of the mono tephras which date from approximately 1200 to 1000 YBP.

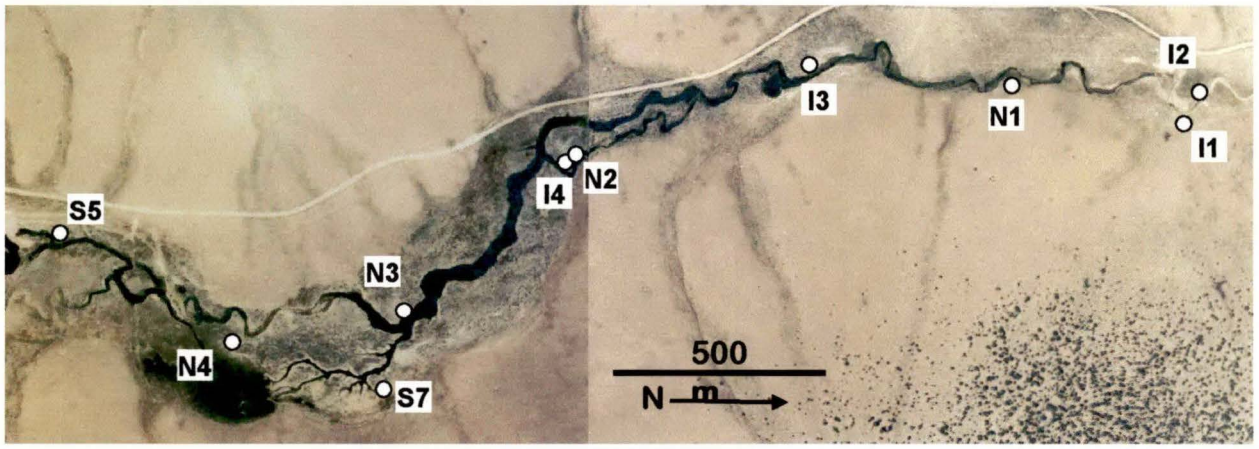

Figure 3. Location and identification of stratigraphic sections in Indian Creek Valley.

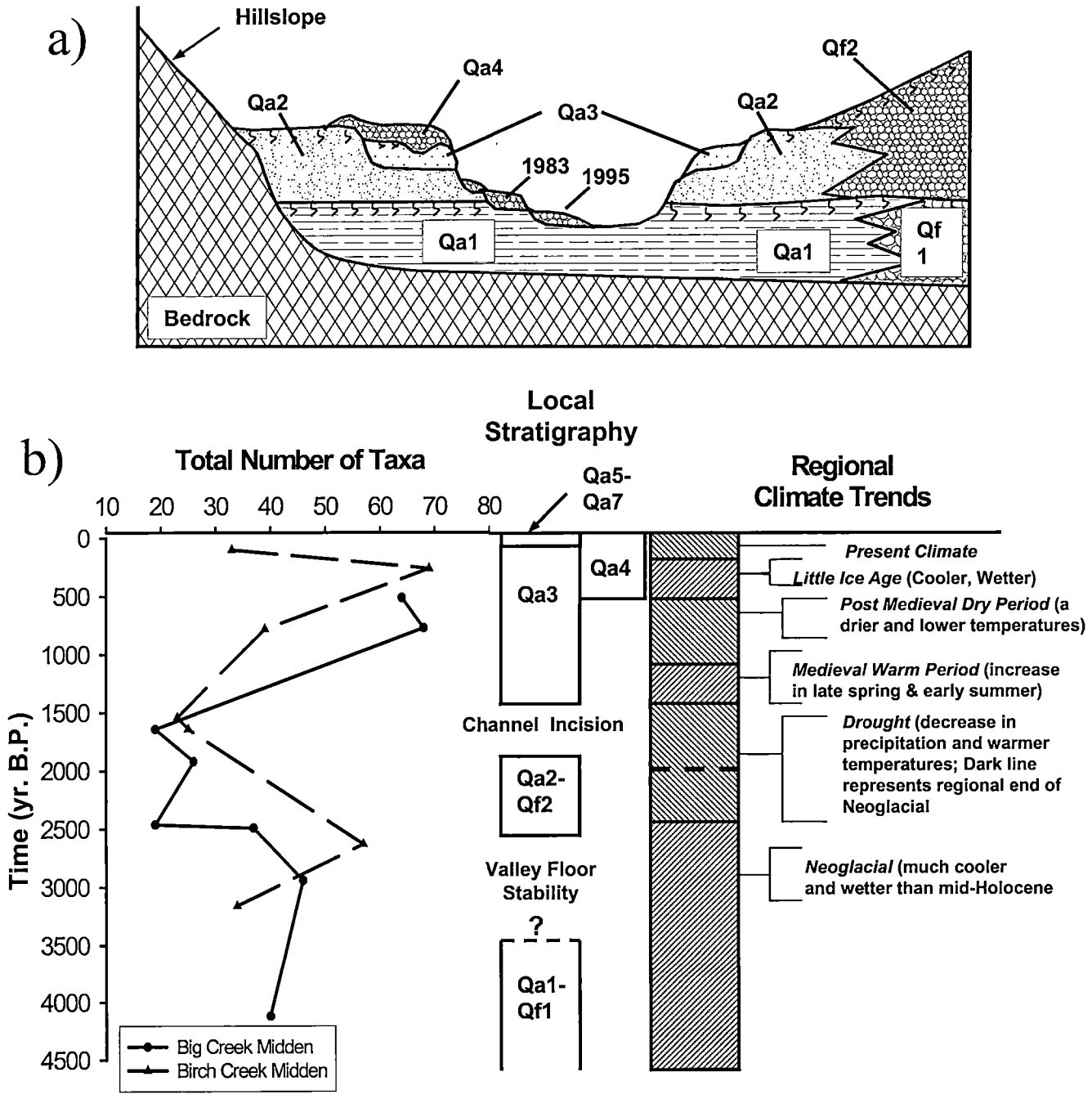

Figure 4. a) Schematic diagram of mid- to late Holocene stratigraphy in upland watersheds of central Nevada (from Miller et al. 2001). b) Relations between alluvial stratigraphic units delineated in central Nevada and the timing of climatic shifts (from Miller et al. 2001).

Qa3 deposits occur both as channel fills cut into Qa2 and as semi-continues deposits that cover the valley floor (and soils) which was once formed by (and in) Qa2. Qa3 is more than is the case many other watersheds in central Nevada and forms a significant part of the bank exposures in areas downstream and within the instrumented region of the valley. It appears that it consists of three separate facies. At the base of Qa3, the unit is characterized by alternating beds of coarse sand and granules separated by thin beds of massive, loam. Overlying this facies is 1-2 m of massive, loamy, gray sediments containing small (< 1 cm) pebbles throughout the material. This facies is most pervasive in downstream areas. Locally, this unit forms a channel that is cut into the underlying material. Similar sediments overlie this unit, but contain reworked ash, which is presumably one of the ash deposits. Where this unit buries the soils of Qa2, the tephra is cleaner and the deposits are commonly characterized by loose sands along the contact with Qa2. If the tephra is one of the Mono ashes, then its age is consistent with that of Qa3 dated using radiocarbon methods in other valleys in the area.

Inset into Qa3 is unit Qa4. This unit is similar to Qa4 described near the mouth of Cottonwood Canyon (Miller et al. 2001), but appears to be of more limited duration. It is also spatially limited. The only location where it was identified was at Section 5 (S5 on Fig. 3). It may be related to channel development on the adjacent fan and, in fact, the orientation of sedimentary structures suggests that the depositing channel is oriented roughly perpendicular to the downvalley direction. Sedimentologically, it is characterized by alternating beds of fine-grained (silt loam) sediments and loose granules. The massive fine-grained units are generally 10-20 cm thick and contain minor amounts of plant debris. The coarse-grained units are moderately well-sorted and clasts are generally <0.5 cm. The largest clasts range up to 3 cm.

Qa5 is overlaps Qa4 and is cut into Qa3. This part of Qa4 is characterized by channel fill deposits exhibits an alternating sequence of fine-grained, organic-rich sediments and thin (<1 cm) sand beds. Abundant organic rich sediments occur within the base of the channel fill at Section 5B. The channel at Section 5 is much larger than at other areas of the valley. In most locations, Qa5 deposits form 1-1.5 m deep channels that dissected the valley floor formed by Qa3. These channels appear as dark colored sediments that overlie Qa3 in a number of locations upstream of the instrumented section. The organic materials yielded a radiocarbon data of 520 +/- 70 YBP, indicating that it is temporally correlative to Qa4 deposits in other areas, and suggests that periods of cut and fill were common within the valley at this time (as it was in many other areas where wetlands were present).

In one region there is a lobate deposit locally preserved on the valley floor which is designated at Qa6. This unit is characterized by loose, horizontally bedded sands and dark gray to black silts with pebbles throughout. Qa6 overlies Qa5, and has been dated to 300 +/- 60 YBP. It is interpreted as a fan-like deposit on the valley floor at the mouth of a discontinuous gully.

This gully may or may not have been the onset of the main integrated drainage system that is now seen in this part of the Indian Creek Valley.

Hydrogeology

Ten transects were established in four reaches of Indian Creek valley with each reach representative of a different stage of valley floor incision (Fig. 2). The emphasis of this discussion is on the three reaches that are in the incised section of Indian valley with the depth of incision greatest upstream. The fourth reach (at transect 10) is in a broad, meadow complex just upstream of headcuts, which form the terminus of the trench system (Fig. 2). Along each transect, groundwater wells were installed on different geomorphic surfaces (i.e., valley floor, trench floor, trench floor terrace) on both sides of the stream. Vegetational composition was determined at each well site. Four or five wells were installed along most transects. In each of the lower three reaches, one transect was instrumented in more detail (transects 3, 5, and 8). Along these transects, nested piezometers were installed on both sides of the trench floor and observation wells were installed nearby up- and downstream of the main transect line. This design permitted a local, three-dimensional view of groundwater flow patterns. A total of 60 groundwater wells were installed at the Indian Creek site. As with the Big Creek site, groundwater levels were measured at least once per month from May to November. Three years of groundwater level data have been collected at Indian Creek.

The depth to groundwater strongly varies with geomorphic position and reach (Table 5.1). In the incised reaches of Indian Creek valley, the depth to the water table is greater from the valley floor, typically 2 to 4 m, than the floor of the incised trench. In contrast, in the unincised meadow complex upstream (transect 10), the mean depth to water table is less than 1 m on the upgradient side of a trench headcut (Fig. 2). The groundwater table is 2 to 3 m lower on the downgradient side of the trench. Along the floor of incised trench, the depth to groundwater increases downstream, ranging from near or at the ground surface upstream to well over 1 m deep in the area downstream.

The position of the groundwater table is significantly more spatially and temporally variable downstream than upstream. For example, over the three year monitoring period (20 water level readings) the water table elevation downstream (transect 3) has ranged about 2.5 m while upstream (transect 8) the water table elevation has ranged less than 0.3 m. On a given date, the water table elevation along a transect typically varies between 0.1 to 0.2 m at transect 8 and about 0.4 m at transect 3. Seasonal variations in the groundwater table become increasingly pronounced with distance downstream from the trench headcuts (Fig. 5). In the upstream reach, the level of the groundwater table elevation is very consistent whereas the downstream reach

Table 1. Mean depth to water table and hydraulic gradients in different reaches of Indian Creek valley (from Jewett et al. 2004).

	Mean depth (m) to water table from valley floor +/- S.D.	Mean depth (m) to water table from trench floor +/- S.D.	Mean water table gradient, down valley	Mean vertical hydraulic gradient, east side of stream	Mean vertical hydraulic gradient, west side of stream
Downstream, T3	3.0 +/-0.84	1.21 +/-0.83	0.0038*	-0.081	no data
Midstream, T5	2.9 +/- 0.21	0.57 +/-0.19	0.010	0.0040	0.0099
Upstream, T8	2.4 +/-0.13	0.15 +/-0.065	0.011	-0.074	0.013
Broad Meadow, T10	0.96 +/-0.32	N.A.	no data	no data	no data

* a negative value indicates a downward groundwater flow component; a positive value indicates an upward flow component

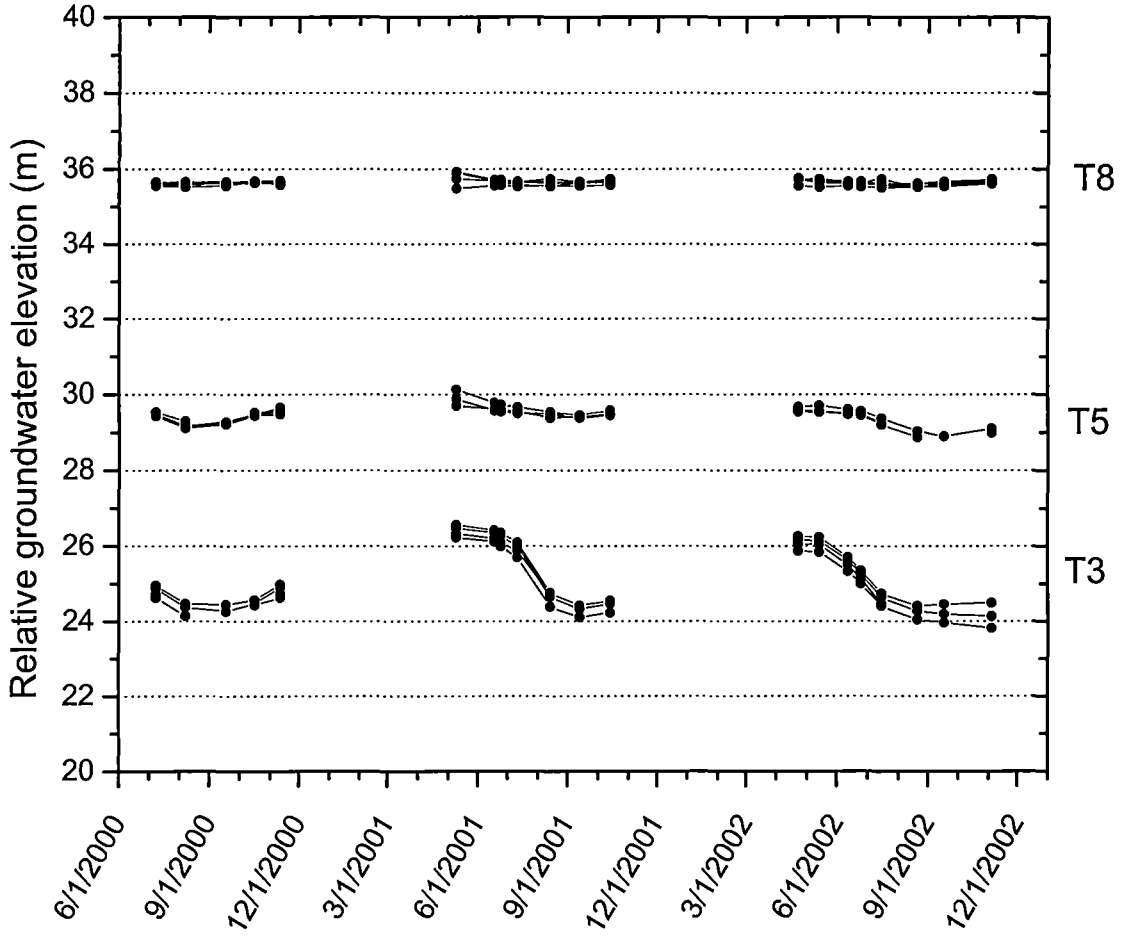

Figure 5. Relative groundwater table elevations during growing season for a cross-sectional set of wells at upstream (T8), midstream (T5), and downstream (T3) sections. The groundwater table at the downstream section exhibits the greatest spatial and seasonal variability (from Jewett et al. 2004).

shows distinct seasonal patterns in the groundwater table with about 2 m of drop over the growing season.

The interaction of groundwater and stream water can be evaluated by examination of water table maps and nested piezometer data. A water table map of the upstream incised study reach, covering transects 7 to 9, indicates a gaining stream (converging groundwater flow) at the upstream end of this reach and a losing stream at the downstream end (Fig. 6). The set of nested piezometers on the west side of transect 8 corroborates this observation by exhibiting an upward groundwater flow gradient (Table 5.1). Elsewhere in the incised portion of the study area, Indian Creek is mostly losing, but the conditions vary with space and time. For example, although the temporal average vertical hydraulic gradients at transect 5 (Table 5.1) indicate upward flow, the gradients are very low and are negative (i.e. downward) as often as positive. The downstream incised reach (transects 1 to 3) is consistently losing with a relatively steep downward gradient.

Groundwater and stream interaction can be further assessed by analysis of the electrical conductivity of water samples. On three dates, groundwater wells and stream water were sampled for conductivity at transects 1 to 9. The conductivity of the groundwater at the upstream and midstream reaches (means +/- SD: 515 +/-106 and 532+/-129 μS/cm, respectively) were significantly higher than the downstream reach and the stream water (means 409 +/-50 and 445 +/-2.8 μS/cm, respectively). The very low variability in the stream water conductivity indicates little influence of groundwater on stream water chemistry over the study reach. The relatively low conductivity of the groundwater downstream is consistent with either the stream water being the source of the groundwater (i.e. a losing stream) or the groundwater being part of a different flow system than upstream reaches.

Geomorphic and Hydrogeologic Setting

In the Indian Creek valley, the characteristics of the groundwater system are best explained by a near-constant supply of groundwater at or above the upstream end of the study site. This is indicated by the steady groundwater table levels found in transects 7 to 9 (Figs. 2 and 5). Furthermore, the absence of seasonal variation in the groundwater table indicates a discharge zone of deep groundwater flow system, which is not depleted by evapotranspiration (Mifflin 1988). These observations are similar to those of Hill (1990) in a study of groundwater discharge in an upland meadow in northwestern Nevada. Hill instrumented a headwaters meadow dissected by a gully with wells and piezometers. Based on physical and chemical hydrologic data, he interpreted the dominant groundwater source to be deeper discharge from fractured rhyolitic bedrock rather than from alluvium and colluvium.

Downstream in the Indian Creek site, the variability of the groundwater table increases and the stream becomes consistently losing. In the middle reach, transects 4 to 6, reversals in

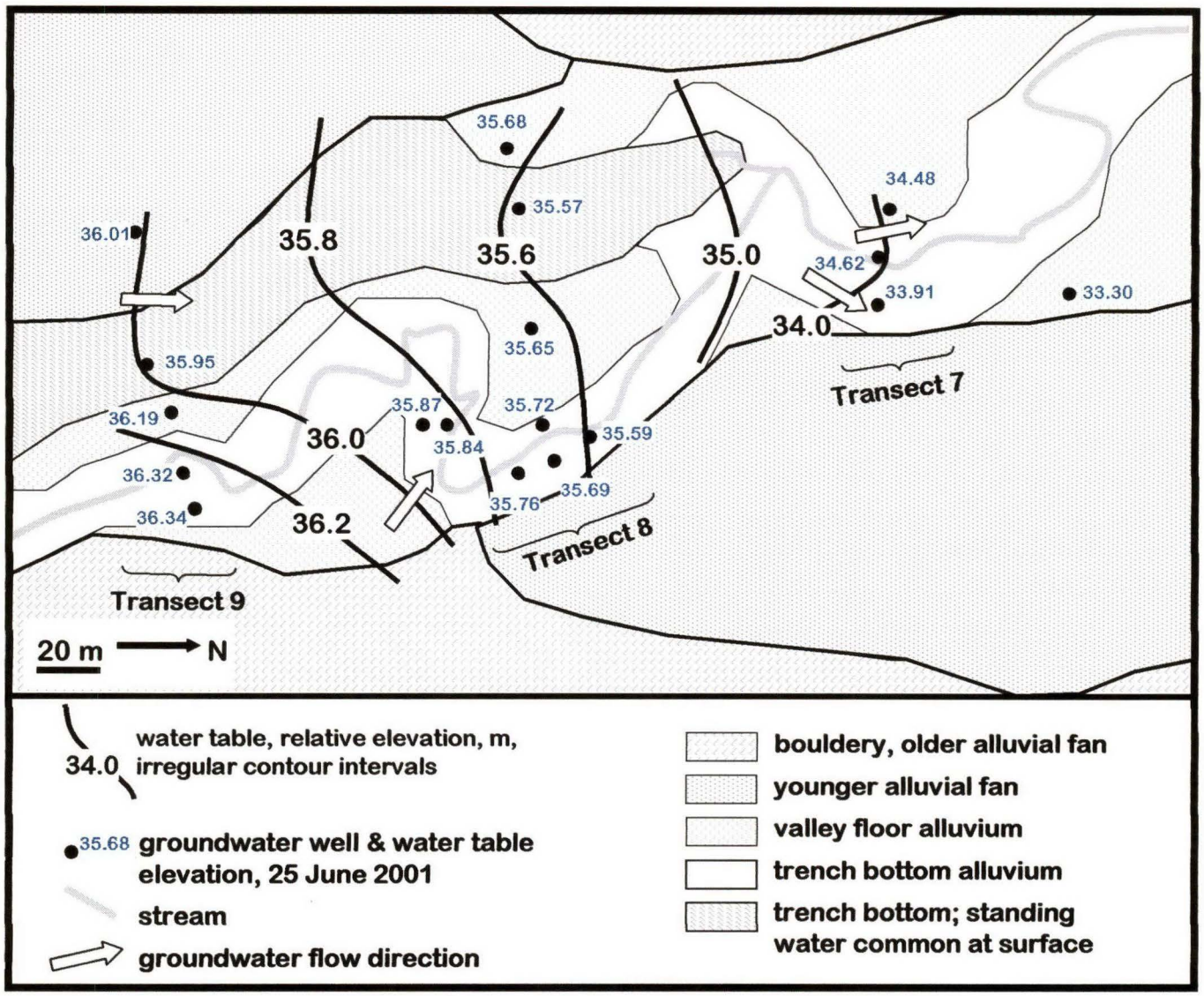

Figure 6. Groundwater table, well locations, and geomorphic units for the upstream section. The stream trends from gaining to losing in the downstream direction over the reach shown; consistent with lateral trends shown, nested piezometers in this reach most commonly exhibit an upward groundwater flow gradient (from Jewett et al. 2004).

vertical groundwater flow directions are common through time. In this area, the lateral, downvalley, and vertical hydraulic gradients are low. Therefore, subtle shifts in the balance of lateral versus downvalley groundwater inputs cause changes in the interaction of groundwater and stream water. Temporal shifts in the location of gaining and losing reaches of a stream is common in the Great Basin (Mifflin 1988). In the downstream reach (transects 1 to 3), the generally dry stream channel, variable groundwater table elevation, and low hydraulic gradient likely reflect an increase in the permeability of subsurface materials caused by the change in geology and the large distance from the upstream, steady groundwater source.

Groundwater discharge in the wet meadow areas is likely due to (1) a decrease in the hydraulic conductivity and connectivity of valley fill deposits at or immediately downstream of the meadows, (2) constrictions in the width and thickness of the valley fill aquifer materials, or (3) a combination of the two. Either of these changes would be accompanied by an increase in the hydraulic gradient near the wet meadow. A dramatic decrease in the ability of the sediments to transmit water could result in groundwater discharge at the surface in order to maintain hydrologic continuity. Geomorphic and stratigraphic evidence indicate that the valley fill deposits are highly complex and spatially variable. This suggests that the hydraulic conductivity and lateral continuity of these deposits also are highly variable and may, in part, be responsible for the presence of wet meadows upstream of the alluvial fans.

Given that most upland meadows in central Nevada occur upstream of side-valley alluvial fans, and that groundwater discharge may be associated with a reduction in the cross-sectional area of the aquifer as a result of bedrock highs, there appears to be a genetic link between the side-valley fans and evolution of the bedrock topography underlying the valley floor. Miller et al. (2001) found that the side-valley fans are composed of sediments from numerous depositional sequences, the most recent occurring between approximately 2500 and 1900 YBP. Thus, fan deposition has been an episodic process throughout the Holocene. It is possible that prior to valley aggradation, scour of the bedrock in the vicinity of the side-valley fans was limited by the delivery and deposition of coarse-grained sediments from the fan basins. Put differently, the fan deposits protected the underlying bedrock from erosion, creating localized highs in the longitudinal configuration of the bedrock topography beneath the existing valley floor.

In the case of Indian Creek valley, however, the origin of the meadow complexes is not clearly related to the position of the side-valley alluvial fans. Lord et al. (in review) suggest that the large basin width, coarse-grained alluvial fans, and low angle slopes in the upper portion of the basin provide ideal conditions for groundwater recharge (Fig. 2). Downstream, the basin and valley width narrow, the bedrock is different, and the sediment cover is thin. These conditions likely cause groundwater flow to converge upgradient of the 'constriction', affording a steady

supply of groundwater. Although the Indian valley meadow complexes are not related to side-valley alluvial fans, the Indian Creek basin geology and topography do serve a similar hydrogeologic function in that this setting causes a convergence and concentration of upgradient groundwater flow. Regardless of the origin of individual riparian meadows in the upland basins, it is evident that the sum of the geologic and topographic conditions associated with the setting must be conducive to supplying ample and steady groundwater—most likely as a discharge area of a large-scale groundwater flow system.

Impact of stream incision on hydrology and vegetation

The entrenchment of much of Indian Creek valley has strongly affected the groundwater and vegetational characteristics of the study site. The depth to the groundwater table is less than 1 m in unincised wet and mesic meadows and typically several meters deep adjacent to incised trenches (Table 5.1). The drop in the groundwater table is apparent from well data (e.g. at transect 10) and by viewing groundwater seeps in trench headcuts, which slant downward in the direction of groundwater flow. Although the main incision at Indian valley resulted in the trench, the trench bottom has been incised a couple of decimeters in places resulting in one or two terraces. As with other meadow complexes in the central Great Basin, vegetation type is strongly correlated with depth to groundwater (Lord et al., in review). Consequently, the vegetation types at Indian Creek correlate with the geomorphic setting because of its relationship to the depth to groundwater (Table 5.2). Vegetation type is most sensitive to the geomorphic setting (i.e., vertical position) in the upstream area where there is less variability in groundwater levels. For example, at transect 7, wet meadow vegetation is present at the lowest level of the trench floor, mesic vegetation is on the trench floor terrace, only 10 to 15 cm above the lowest level, and sagebrush is dominant above the trench on the valley floor.

Characterization and evolution of trenches and channels in Indian Creek valley

In Indian Creek valley, there is a continuum of trench sizes and forms: they range from shallow, discontinuous trenches to an integrated, deep, continuous trench system (Figs. 2 and 7). In addition, there are some surface water channels on the valley floor and within the trenches. All of the trenches and channels in Indian Creek valley were observed; the trenches were qualitatively categorized based on shape and size characteristics. Four types (A, B, C, and D) of trenches were described for size, geomorphic characteristics (i.e. slopes, slump blocks, surface water channels, etc.), and hydrologic characteristics. Qualitative and quantitative descriptions of the trench types are summarized in Table 3. Along with size, the trench types are most easily distinguished based upon how actively the trench walls are enlarging due to slumping, most likely induced by groundwater sapping.

Indian Creek valley does contain some ephemeral stream channels, especially in the upper portion of the valley (Fig. 7). These channels are most common along the margins of the

Table 2. Depth to water table and dominant vegetation type (TWINSPAN) at different geomorphic positions at an upstream and downstream transect. Water table values are mean +/- standard deviation. Vegetation types and analysis follow Weixelman et al. 1996 (from Jewett et al. 2004)

	Upstream Reach Well Sites		
Well #:	7D	7B	7C
Geomorphic setting:	valley floor	trench floor: upper terrace	trench floor: lower terrace
Depth to water table:	1.65 +/- 0.06	0.44 +/- 0.23	0.35 +/- 0.07
Vegetation type:	*Artemisia tridentata / Leymus cinereus*	mesic meadow	wet meadow

	Downstream Reach Well Sites		
Well #:	3D	3C	3B
Geomorphic setting:	valley floor	trench floor: upper terrace	trench floor: lower terrace
Depth to water table:	1.44 +/- 0.76	1.25 +/- 0.87	1.14 +/- 0.88
Vegetation type:	dry meadow & *Artemisia tridentata / Leymus cinereus*	dry meadow	wet & dry meadow

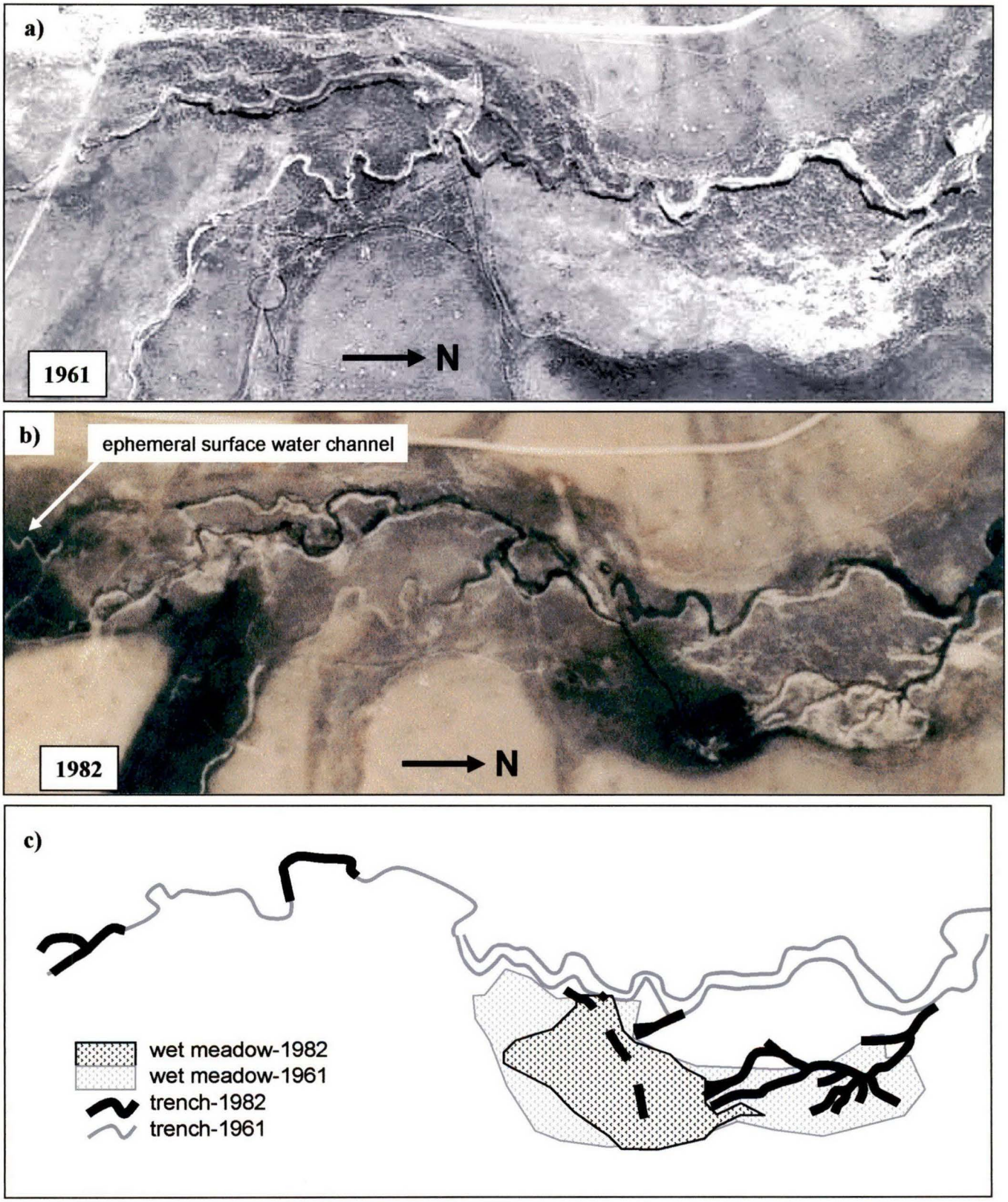

Figure 7. Actively incising meadow complex. Vertical aerial photos of upstream portion of study area in 1961 (a) and 1982 (b). A new trench system developed almost entirely over the 21 year period (northeast portion of photo). Note that a decrease in wet meadow area coincides with the new trenches (c).

valley floor, range in bankfull depth from about 0.5 to 2 m, and have a riffle-pool geometry. Some of these channels are shallow and discontinuous, and terminate in sediment fans (Fig. 8). Artificial "check" dams block shallow channels in over a dozen places. At many of these sites, the check dams are paired with small, straight dug channels to divert water—presumably for irrigation or to supply water to cattle. At least three of these diversion channels coincide with the start of major headcuts of the integrated trench system in lower Indian Creek valley.

The rates of growth of the trenches in Indian valley are not known, but it is clear from a preliminary analysis of historical aerial photographs that they have enlarged significantly over the past several decades. For example, well over 500 m of trenches developed between 1961 and 1982 (Figs. 7). It is also clear from the photos that entrenchment of the valley floor drops the water table below necessary levels for wet meadow vegetation. The area loss of wet meadows between 1961 and 1982 coincides with the location of the new trenches (Fig. 7). Wet meadow complexes were also present on the valley floor farther downstream. This is indicated by active trenches, the presence of meadow paleosols on the valley floor of entrenched areas, and the abrupt change in vegetation, from wet meadow complexes to sagebrush, at headcut positions. This vertical displacement of broad meadow complexes downward to strip meadows on the trench floor has resulted locally in an approximately 90 % loss of area in the meadow complexes where the valley has been incised. As discussed above, it is probable that the incision of the valley floor will continue in the future as it has in the past. Additionally, the hydrologic and vegetational characteristics that exist downstream, will migrate upstream in response to the new incision (Fig. 9). Eventually, over a long time scale (at least hundreds of years), it is probable that the trench systems will widen to span the valley floor and once again support broad, wet meadow complexes.

Processes and Evolution of Incised Trenches

Many incised trenches at Indian valley are actively migrating upgradient (Fig. 7). Trench sides are steep and angular slump blocks are common at active seeps (Table 3). This form is characteristic of erosion caused by groundwater sapping (e.g., Howard and McLane 1988; Kochel et al. 1988; Higgins et al. 1990; Pederson 2001). Once incision is initiated, the process is self-enhancing, commonly causing an increase in erosion rates with time. The incision causes lowering of the groundwater table and an increased convergence of groundwater toward the headcut (Dunne 1990; Montgomery 1999; Pederson 2001). Continued effectiveness of this process requires the removal of failed debris from the slope base by surface waters (Dunne 1990; Higgins et al. 1990). If the failed material is not removed, it may result in discontinuous gullies (Montgomery 1999). The effectiveness of the sapping process is further enhanced because the drop in the water table can cause a decrease and/or change in vegetation type (Keller et al. 1990). In the case of Indian Creek, the drop has resulted in a shift in vegetation type from wet meadow to dry meadow, mesic meadow, or basin big sagebrush meadow (Table 5.2, Fig. 7). In meadow

Figure 8. Sediment fan at downstream end of discontinuous emphemeral stream channel (notebook in mid-photo for scale).

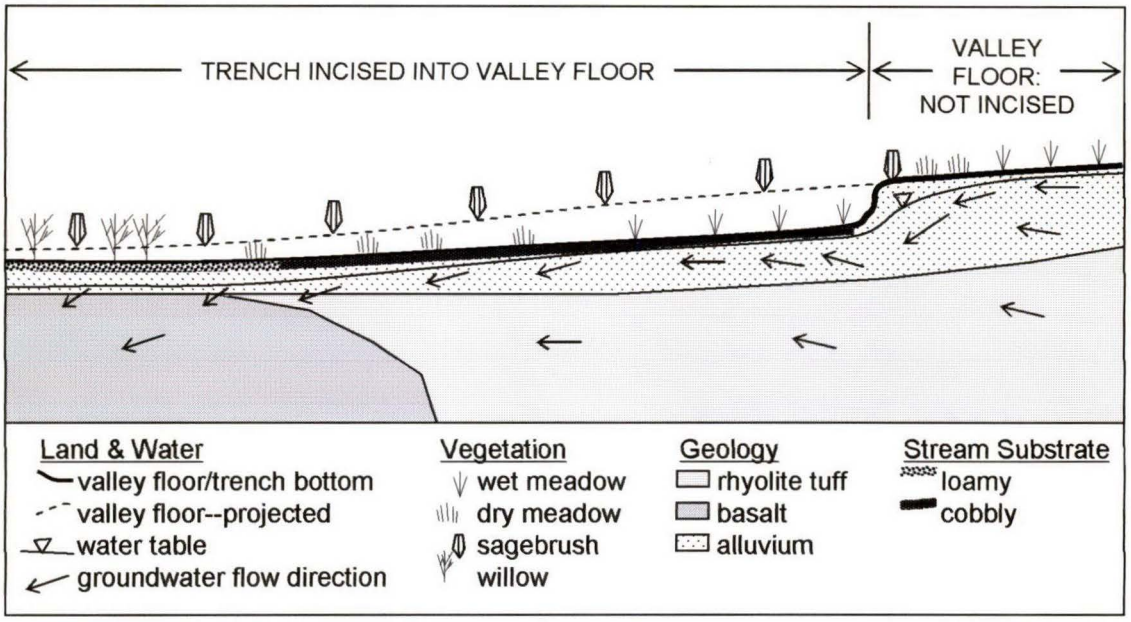

Figure 9. Schematic cross section through the Indian Creek valley study area showing mutual relationships of bedrock, surface sediment, water table, groundwater flow direction, trench depth, and vegetation (from Jewett et al. 2004).

TABLE 3. Trench Types	Small-scale >>>> TRENCH TYPES >>>> Large-scale			
	A	**B**	**C**	**D**
Integration	Discontinuous, isolated	Integrated	Integrated	Integrated
Relation to groundwater	Most TFs decimeters above GWT, but some GWS & piping at TW bases	Most TFs decimeters above GWT, but some GWS at TW bases	GWT is at or just below TF. GWS at headcuts very common	GWT is at or just below TF. Little to no evidence of GW seeps on TW
Trench wall geometry	Relatively straight; not dissected by slump scars or gullies	Irregular, scalloped with slump scars	Irregular, scalloped with slump scars	Relatively straight, locally irregular due to dissection by gullies
Slump activity	Some minor undercutting at active headcuts; no slump blocks	Abundant, angular, large slump blocks on TW slopes and on some TFs	Abundant, rounded slump blocks on TW and at base; TF is flat	Little to no evidence of recent slump scars or blocks
Typical size	Width: 3-5 m; Depth: 0.2-0.5 m	Width: 5-12 m; Depth: 1-2 m	Width: 8-15 m; Depth: 2-3 m	Width: 15-30 m; Depth: 2.5-6 m
Evidence of SW channels	None in TF; some have minor rills leading to headcuts but others have none	None in TF; some have minor rills leading to headcuts but others have none	None in TF; some have minor rills leading to headcuts but others have none	Relatively narrow sections of TF commonly contain discontinuous SW channels
Other	TW height is greatest at headcut & decreases down valley.	Many TFs are above elevation of TF types C & D--similar in form to hanging valleys.	In examination of 13 headcut areas, the GWT was within 15 cm of TF at all sites.	Dry, cohesive upper TW; some sagebrush on slopes
Picture				
Interpretation	Incipient, well developed incised trenches. Growth is limited by GW supply and adequate bank height to trigger slope failure.	Forms of trenches indicate rapid enlargement by GW sapping and slumps when active, but are likely only active during extreme wet years.	Most are seasonally active growing trenches with slumping triggered by GW seeps; activity is concentrated in headcuts.	Major trunk system of trenches; TWs are stable with respect to instability caused by GW seeps. TF contains wet meadows and discontinuous, shallow SW channels.

Key: GW: groundwater; SW: surface water; TF: trench floor; TW: trench wall; GWT: groundwater table
GWS: groundwater seeps (i.e. diffuse groundwater flow out of slope face)

complexes, soils supporting wet meadows have greater bank strength than dry meadow soils and, therefore, are less prone to failure (Micheli and Kirchner 2002a, 2002b). In a study of the influence of bank erosion rates in a meadow complex of California's Sierra Nevada range, Micheli and Kirchner (2002b) found that dry meadow banks retreated six times faster than wet meadow banks. In sum, once entrenchment of a meadow complex initiates, it is highly likely to continue until it reaches a new stable state (Schumm 1999).

It is clear that groundwater induced slope failure is important in the entrenchment of Indian Creek valley. Previous studies on groundwater sapping, summarized above, have identified numerous variables that control the effectiveness of this process: groundwater flow convergence, surface water removal of slump debris, a threshold bank height and strength, and bank vegetation type. In Indian Creek valley, trench types B and C (Table 3) are the most active. These trenches are deep enough to have cut through the high-strength root zone of wet meadows and have headcuts in a position to collect significant groundwater flow. Type B trenches differ from type C in that their trench bottoms, in many places, are elevated above the main trench floor (of types C and D) and are choked with angular slump blocks. These characteristics indicate that the hydrologic conditions necessary for entrenchment, a higher groundwater table and/or some surface water flow, were not of enough duration or frequency to cause further incision. Thus, these trenches (type B) are likely active only during exceptionally wet years.

The headcuts of type C trenches (Table 3) all appear to be very recently active, indicating that the frequency and/or duration of necessary hydrologic conditions is met most years. This conclusion is supported by Johnson (2004), who completed a detailed study of a headcut of a type C trench in Indian Creek valley. The purpose of his study was to model the hydrologic conditions necessary to trigger slope failure at a headcut. This study indicates that bank failure will occur when the groundwater table is about 0.5 m higher than levels typical of July—a time of seasonal low groundwater tables. It is likely that this threshold condition is met most during most spring seasons, based on year-round groundwater level data in central Nevada.

The most stable trenches in Indian Creek valley are the largest, type D, which show little evidence bank failure caused by groundwater conditions. More recent entrenchment of the valley has resulted in a trench network that captures groundwater that would have previously fed into the large trunk trenches.

The specific triggers that initiate trench development in Indian Creek valley are not known, but it is very likely that land-use activities within the valley have accelerated and triggered some of the activity. Evidence for this is most clear at several check dams, described earlier, where dug diversion channels coincide with the start of a trench. This diverted water probably enhanced the ability of surface flow to remove failed debris from trench bottoms. In

addition, diversion and ponding of water would have altered the elevation of the water table and affected sapping processes.

Land use activities that trigger entrenchment would not be so important if Indian Creek valley was not ideally suited, geologically and hydrologically, for groundwater sapping related processes. The stratigraphy of the Indian Creek valley fill and other work in southwestern U.S. suggest that episodes of incision of the valley alluvium have occurred in the past and that incision is related to climatic change and basin sediment supply (Chambers et al. 1998; Elliott et al. 1999). Upland axial valleys demonstrate different degrees of sensitivity to incision (Miller et al. 2001). Indian Creek valley is very sensitive to entrenchment driven by groundwater sapping. Favorable conditions for sapping present in Indian Creek valley include convergence of groundwater, unconsolidated material, a critical bank height to induce slope failure, and enough surface flow to remove failed debris (Kochel et al. 1988; Dunne 1990; Nash 1996; Pederson 2001).

MANAGEMENT AND RESTORATION IMPLICATIONS

Understanding the geomorphic and hydrogeologic controls on the evolution of riparian habitat in the Great Basin of Central Nevada can be used to develop watershed-scale management strategies intended to maintain or restore these ecosystems. The following questions should be addressed in considering management options:

1. What are the hydrogeologic conditions that led to the formation of meadow complexes?
2. What are the base level controls on the valley segments and stream reaches of interest? What are the base level controls on the groundwater regime?
3. What is the susceptibility of the soils/sediments/bedrock underlying the meadows to incision by surface water erosion or groundwater sapping?
4. What is the sensitivity of the existing vegetation to change with changes in the groundwater-regime?

Conceptualizing and characterizing surface water and groundwater interactions at the valley segment and stream reach scales are an essential step in restoring riparian ecosystem process and pattern (Woessner 2000; NRC 2002). The complexities of the groundwater-surface water interactions in riparian meadow systems in the Great Basin are apparent from this study. The hydraulic conductivity, connectivity, and geometry of the alluvial aquifer materials determine the spatial and temporal characteristics of groundwater flow. These geologic and hydrogeologic conditions must be understood so that the appropriate hydrologic regime (both surface and subsurface flows) can be managed or reestablished through restoration activities.

Additional studies to investigate smaller scale stream and groundwater mixing in the hyporheic zone and to evaluate the influence of bedrock structure at these and other riparian meadow study sites are under design.

Determining the base level controls on stream and groundwater levels is important for maintaining sustainable riparian ecosystems and developing restoration strategies for degraded ecosystems. The potential maximum depth of stream entrenchment in upland watersheds must be assessed at sites warranting restoration. Restoration alternatives need to be evaluated with respect to this potential base level so that viable alternatives can be identified. For example, the selection of channel or stream bank stabilization alternatives depends on the likelihood of these stabilization efforts being undermined by erosion associated with future high intensity rainfall/runoff events. Because groundwater levels will likely adjust themselves to newly established base levels following stream incision, local hydrogeologic and stratigraphic controls also must be considered during the base level evaluation.

It is necessary to understand the incision processes and sensitivity of a stream system to incision because of the importance of streams in establishing local base levels. Upland basins of the central Great Basin may be grouped by characteristics that correlate with sensitivity to incision. Riparian ecosystems that are more sensitive require careful management and, if degraded, will require more effort to restore. Furthermore, incision of the valley floor by stream downcutting versus entrenchment driven by groundwater sapping require different management strategies. Stream downcutting progresses by the upstream migration of knickpoints along the stream bed. To slow incision of riparian meadows in these areas, the knickpoints should be stabilized, especially in and immediately downstream of the meadow complexes. In meadow complexes prone to or exhibiting signs of groundwater sapping, the headcuts must be stabilized. As described previously, once incision by groundwater sapping is triggered, the process is self enhancing and will be difficult to stop. Understanding the directions of groundwater flow and stratigraphy is important, because trenches extend preferentially along pathways of higher groundwater discharge (Kochel et al. 1988). Any land use activity that concentrates either groundwater or surface water is likely to accelerate the entrenchment of the valley.

The sensitivity of plant species composition to the groundwater regime is obvious at Indian Creek and other study areas. Vegetation type and pattern is determined by the hydrologic regime in riparian areas of the semi-arid and arid U.S. (Stromberg et al. 1996; Martin and Chambers 2001). A lowering of the water table following stream incision can reduce the areal extent of meadow and other riparian vegetation types, and significantly alter plant species composition and diversity. In order to accurately evaluate the effects of stream incision and the subsequent lowering of water tables on riparian plant species and communities, we must first understand the relationships among vegetation composition and pattern and groundwater

regimes. This issue is further complicated in Indian Creek valley because it is a refuge for threatened Columbia Spotted Frog. At present, the frogs are more abundant within the trench systems—the disturbed system, versus the valley floor, because of they offer greater hydrologic stability (Hatch 2004).

Stream incision is a major issue affecting the sustainability of riparian ecosystems in upland watersheds in central Nevada. In order to protect threatened riparian ecosystems and to restore degraded riparian ecosystems, one must have a thorough knowledge of the hydrologic regime. In fact, a National Research Council report on riparian area functions and management strategies states that "repairing the hydrology of the system is the most important element of riparian restoration" (NRC 2002). Still, the relationship between hydrology, geomorphology, and vegetation patterns and dynamics is complex (Patten 1998; Tabacchi et al. 1998). A successful riparian ecosystem management and restoration strategy requires a thorough and integrated understanding of all of these issues.

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